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# RENEW v3.2 User's Manual, Maintenance Estimation Simulation for Space Station Freedom Program

Bruce L. Bream
Lewis Research Center
Cleveland, Ohio

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RENEW Version 3.2 User's Manual
Maintenance Estimation Simulation Model
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## FOREWORD

Lewis Research Center (LeRC) engineers developed the RENEW simulation software in response to the need for greater fidelity in modeling the 30 year mission and resupply environment for Space Station Freedom. While the software is focused on resupply of on-orbit replaceable units of the Space Station Freedom it uses modeling techniques that apply to other mission scenarios.

## ACKNOWLEDGEMENTS

The RENEW software has been a collaborative effort between LeRC and SAIC (Scientific Applications International Corporation) engineers. The modeling techniques were developed and the software evaluated with the assistance of Edward Zampino and David Hoffman from NASA Lewis Research Center, and W. James Dorcey from SAIC.

# 1.0 INTRODUCTION

RENEW is a maintenance event estimation simulation program developed in support of the Space Station Freedom Program (SSFP). This simulation uses reliability and maintainability (R&M) and logistics data to estimate both average and time dependent maintenance demands. The simulation uses Monte Carlo techniques to generate failure and repair times as a function of the R&M and logistics parameters. The estimates are generated for a single type of orbital replacement unit (ORU).

The RENEW simulation gives better estimates of performance over a given time period than steady-state average calculations since RENEW uses a time-dependent approach and depicts more factors affecting ORU failure and repair. RENEW gives both average and time dependent demand values. Graphs of failures over the mission period and yearly failure occurrences are generated. The average demand rate for the ORU over the mission period is also calculated. While RENEW displays the results in graphs, the results are also available in data tables.

# 2.0 PROGRAM OVERVIEW

RENEW is a compiled program written with Microsoft QuickBASIC. It runs on an IBM-286/386 system with 640K memory, CGA or VGA graphics card, and DOS 3.0 or higher operating system. The program is a single file "RENEW32.EXE". Data files are produced by the program for storage of input and output data. The RENEW program must be on the same DOS drive as the data files. See Appendix B for more information regarding installation and files.

The process of using RENEW starts with keyboard entry of the R&M and operational data. Once entered, the data may be saved in a data file for later retrieval. The parameters may be viewed and changed after entry using RENEW. The simulation program runs the number of Monte Carlo simulations requested by the operator. Plots and tables of the results can be viewed on the screen or sent to a printer. The results of the simulation are saved along with the input data. Help is provided with each menu and data entry screen.

In this manual, *menu titles* and *screens* are shown in italics. Menu selection keys are shown enclosed by brackets [] followed by the menu name in brackets *{}*. Selections are made by typing the menu selection key followed by the [Enter] key on the keyboard. Typing only the [Enter] key at the "Selection" prompt returns the previous menu.

# 3.0 USING RENEW

## 3.1 RENEW Selections

There are two forms of the *Main Menu* depending on whether data has been entered or retrieved. The first screen displayed on executing RENEW32 from DOS does not have selections to [L]ist/change data, view Simulation [R]esults or [E]xecute the simulation. Once data is input, these selections are added to the menu.

The Data and Files selections provide a means for [K]eyboard Data Input or [F]ile Data Input. The data and results may be [S]aved after entry or simulation execution. A special [B]atch and Summary files menu allows processing of multiple data files. Text files, including all the RENEW input data and output reports, may be viewed with the File Viewer [FV]. With the [F] and [FV] selections, files can only be selected from the current default DOS directory. The default can be changed using [CD] Change Directory. The current default DOS directory is displayed on the screen below this selection.

```
Renew Simulation - V3.2 - Main Menu

DATA AND FILES
* [K]eyboard Data Input           [B]atch and Summary files
* [F]ile Data Input               [FV] File Viewer
  [S]ave Input Data and Results   [CD] Change Directory
                                       {D:\RENEW}
DATA VALUES & FUNCTIONS
* [C]onstants                     [L]ist/Change Parameter Values
* Resource [V]alues               [D]isplay Functions


SIMULATION RESULTS
  [P]lot Histogram                [A]verage Resupply and Maintenance
  [R]esulting Statistics          [Y]early Event Estimates


[H]elp                            [E]xecute Simulation

[Q]uit

* these selections affect simulation results
```

Main Menu

## 3.2 Entry of R&M Data

The original R&M data for an ORU must be supplied through the keyboard by selecting [K]eyboard input *{Main Menu}*. Data validity checks are made as the data is entered. If an entered value is incorrect (e.g. MTBF < 0), the operator is prompted with a description of valid values for the parameter. Upon typing only the <Enter> key a help prompt is displayed and the data may then be entered using this as guidance. The prompted data items are listed and described in Appendix A. Once data has been entered, it can be saved and later retrieved for modification or re-execution by the simulation (Figure 1).

The [L]ist/Change Data selection *{Main Menu}* can be used to view or change data values. This allows verification and editing of entries.

```
Renewal Simulation - V3.2 - List/Change Parameters           Run Date: 10-27-1992
[NAM]  ORU Name                   ORU_1            ORU  Start
[TYP]  ORU Type                   EL - Electrical  No.  Time
       No. of ORUs                6                1    0
[ST]   Start times                                 2    0
[EP]   Prob. of Early Failure     .05              3    1.5
[EL]   Early Mean Life            1 year           4    1.5
[ES]   Early Shape                .4               5    4
[MT]   MTBF Type                  Constant         6    4
[MTBF] MTBF                       35 years
[DC]   Duty Cycle                 1
[MMD]  MTBF-Micrometeroid/Debris  1E+29 years
[WT]   Wearout mean life type     Constant
[WL]   Wearout Weibull Mean Life  15 years
[WF]   Failure Free Period        0 years
[WS]   Wearout Weibull Shape      10
[RD]   Replacement Downtime       0 years
[TIM]  Mission Time               30 years
[ND]   No. of Divisions/year      1
[NS]   Number of Simulations      1000
[RR]   Replacement Ratio          .8
[K]    K-Factor                   1.63
Enter abbreviation of parameter to change
```

List/Change Parameters Menu

While the major set of R&M data is entered through the [K]eyboard selection *{Main Menu}*, the [C]onstants and Resource [V]alues *{Main Menu}* choices allow entry of other data that affect the results.

The *Constants Menu* allows setting the default values for various types of K-factors used to modify the Mean Time Between Failures (MTBF) and mean life parameters and the replacement ratio. All of the constants have a default of 1 which effectively removes these from the simulation. Changing these values will have an effect on the resulting base number of failures. If any changes are made, the results will be erased and the simulation will have to be re-run. The default K-Factor is assigned to an ORU on keyboard entry according to the ORU type indicated. The defaulted K-factor value can be changed with the K-Factor [K] selection on the *List/Change Parameters* Menu. All of the factors can be set to default values with the choices at the bottom of the screen. The Replacement Ratio [RR] may also be set from this menu. Once set, these values will be applied to each data set entered using the [K]eyboard selection *{Main Menu}*.

```
Renewal Simulation - V3.2 - Constants

Reliability Growth:
  1st failure (E1)                  3.3
  2nd failure (E2)                  2.17
  3 and more  (E3)                  .6666667

K-Factors:
  Mechanical (Kme)                  1
  Structural (Kst)                  1
  Structural-Mechanical (Ksm)       1
  Electrical (Kel)                  1
  Electro-Mechanical (Kem)          1
  Electronic (Kec)                  1

Replacement Ratio                   .8

Set all factors to 1.0  (R1)
Set all K-factors to 2.0  (R2)
Set all factors to EMST values (EMST) - Jan 91 Draft Report
Set all factors to EMTT values (EMTT)
Set all factors for Work Package 4 (WP4)
```

Constants Menu

The *Resource Values* menu contains mass, Mean Time To Repair (MTTR) and crew parameters. The MTTR parameter will affect the simulation through the amount of downtime. The mass and crew values are only used in calculations based on the final results and are not used during the simulation.

If any changes are made to the value of the parameters in the *List/Change Parameters*, *Constants*, or *Resource Values* menus, the existing results of the simulation are erased. If this were not done, the results would not match the input data. The user is cautioned to save the results before changing data values.

```
Renewal Simulation - V3.2 - Resource Values

For ORU:  ORU_1

ORU Mass (M)                    30 pounds

Mean Time To Repair (MTTR):
   EVA      (E)                 .6 hours
   Robotic  (R)                 0 hours
   IVA      (I)                 0 hours

Number of Crew:
   EVA      (EC)                1
   IVA/Robotic Crew (IC)        0


[H]elp

NOTE: * * Changing resource values will erase current results * *

Enter abbreviation of parameter to change
  or <Enter> for no change:
```

Resource Values Menu

Some of the parameters in the previous data entry menus may be removed from the simulation by using appropriate values. This allows execution of the simulation when not all of these parameters are known or needed. Suggestions are shown below:

| Parameter | To Remove from Simulation |
|---|---|
| Early Failures | Set early failure probability (EP) to 0 |
| K-factors | Set to 1 |
| MTBF | Set to 1E+29 |
| MTBF for Micrometeroid/Debris | Set to 1E+29 |
| Reliability growth factors | Set to 1 |
| Wearout | Set mean life to a couple of multiples of the mission time, Set shape to 20 |

For example, if an ORU is only modeled with a wearout distribution, the Early Failure Probability parameter, [EP], should be set to zero and the MTBF should be set to 1E+29. This will remove the influence of these parameters on the simulation.

The [D]isplay Functions menu *{Main Menu}* provides plots of the [R]eliability, [H]azard, and [P]robability density functions for the composite distribution (Figure 2). These curves will give an indication of the shape of the distributions that will be used in the simulation with the given input parameter values. This selection is not available when variable MTBF or variable mean life is used.

## 3.3 Executing the Simulation

The simulation may be [E]xecuted *{Main Menu}* once data has been either entered by keyboard or retrieved from a data file. The *List/Change Parameters* screen is displayed for information with the current simulation number displayed at the bottom of the screen during execution. Typing any key will cause the simulation to stop and return to the *Main Menu* with input data preserved but no results. The results are not saved to a disk file until the user selects [S]ave Input Data and Results *{Main Menu}*.

## 3.4 Simulation Results

Choices to view the results of the simulation are presented on the *Main Menu* once the simulation has completed execution. The results are available by topic in both graphical and report format. Graphs can be printed by typing a "*" to "Print" when the graph is displayed on the screen. The only graphics printer format supported is an HP laserjet. The resolution is defaulted to 75 dots per inch but can be changed to 150 dots per inch by typing [*] *{Main Menu}*. Other results and files are written in ASCII and contain no embedded printer codes. A set of data and results files under the base file name "TEST" are contained on the distribution diskette with the RENEW software. Data and results in the .RD3 file can easily be imported into spreadsheets for further analysis.

### 3.4.1 Failure Event Histogram

Choosing [P]lot Histogram *{Main Menu}* will display a histogram of the average number of failure events per year (Figure 3). The initial histogram displays the total events curve along with a second curve depicting the events generated by the highest contributing factor (early, random or wearout). The curves for [E]arly, [R]andom, or [W]earout will be displayed by typing the first letter shown *{Plot Histogram}*. The percentages of the total caused by each type of failure event (early, random, wearout) are shown.

### 3.4.2 Resulting Statistics

Choosing [R]esulting Statistics *{Main Menu}* will give a summary page followed by a number of pages of raw simulation results. The summary page gives:

Total Mission Results

- Average number of Failure Events per total mission
- Standard deviation of average failure events due to the simulation
- Mean Time Between Failure Events (MTBFE) over the mission
- Early, Random, Wearout Percentages based on the number of failure events
- Average No. of Maintenance Actions
- Mean Time Between Maintenance (MTBM) over the mission
- Number of Replacements
- Mean Time Between Replacement (MTBR) over the mission

Yearly Results

- Maximum Failure Events/year
- Year of maximum Failure Event/year occurrence
- Average Failure Events/year

Availability

- Total Available Operating Time for all ORUs
- Total ORU Uptime and Downtime
- ORU Availability based on uptime and downtime
- ORU MTBFE based on uptime and downtime

The [I]nformation selection *{Resulting Statistics}* should be used to view an interpretation of this data on three *Results Information* screens.

```
Renewal Simulation - V3.2 - Results

ORU:  ORU_1        Datafile name: ORU1.RD3                Run Date: 10-27-1992

TOTAL MISSION RESULTS
  Failure Events:                    17.911               MTBFE: 1.674948 years
     6.2% Early            (Std Dev= 2.227564 )
    68.0% Random
    25.8% Wearout
  No. of Maintenance Actions:        17.911
  No. of Replacements:               14.353

YEARLY RESULTS
  Maximum Failure Events/year:       .861 occurs at 5 years
  Average Failure Events/year:       .5970333

AVAILABILITY
  Total Available Operating Time:    169            ORU-years
  Total ORU Uptime:                  168.9988       ORU-years
  Total ORU Downtime:                1.226781E-03   ORU-years
  ORU Availability:                 0.999993
  ORU MTBFE:                         9.435474        years
```

Resulting Statistics Screen

The raw simulation data follows this menu in three tables before returning to the *Main Menu*:

Simulation Event Data

- This data is used to generate the [P]lot Histogram *{Main Menu}*.
- The columns list the time bin with the total, early, random, and wearout failure events per bin.

Yearly Failure Event Data

- This data is used to generate the plots in the *Yearly Event Estimates* menu.
- The listing shows the number of simulations where a particular number of failures occurred (e.g. 0 failures occurred in 960 out of a 1000 simulations with 1 failure in 40 of the simulations).

Yearly Replacement Event Data

- This data is used to generate the plots in the *Yearly Event Estimates* menu.
- The listing shows the number of mission simulations where a particular number of replacements occurred.

The replacement event data will vary from the failure event data when the replacement ratio *{List/Change Parameters Menu & Constants Menu}* is not 1.

### 3.4.3 Average Resupply and Maintenance

The [A]verage Resupply and Maintenance *{Main Menu}* selection gives a listing of averages over the mission and the simulation parameter values used to base these calculations.

Averages Per Year Over the Entire Mission

- Annual Resupply Mass calculated from the replacement events per year, and ORU mass.
- Mean Maintenance Time per Year for External Vehicular Activity (EVA), Internal Vehicular Activity (IVA), and Robotic from the maintenance events per year and the Mean Time To Repair (MTTR).
- 80% Probability of Sufficiency (POS) Replacement Quantity based on the average replacement events per year and standard deviation of failure events from the simulation.

Average events per year, starting with years 3 and 4 through mission end

- These figures are calculated from a sum of the total simulation event data over the years of interest. This time segment was created to give an average event value in the operation phase after the 3 to 4 year SSF assembly phase.

```
Renewal Simulation - V3.2 - Average Resupply and Maintenance


Averages Per Year Over a 30 year Mission:
  Annual Resupply Mass:            14.3 pounds

  Mean Maintenance Time/year:          EVA          0.4 hours
                                       Robotic      0.0 hours
                                       IVA          0.0 hours

  80% POS replacements/year:      .666667

Averages
For 3 through 30 years:           .631 events/year
For 4 through 30 years:           .6340769 events/year

Based on:      .5970333 average maintenance events per year
               Replacement ratio of .8
               .4776267 replacement events per year
               .6 hour EVA time of 1 crewmember
               0 hour Robotic time of 0 crewmembers
               0 hour IVA time of 0 crewmembers
               30 pound ORU mass
```

Average Resupply and Maintenance

### 3.4.4 Yearly Event Estimates

The [Y]early Event Estimate *{Main Menu}* selection gives a menu of selections that provide statistics and curves for individual years during the mission. Selections from the *Yearly Event Estimates* Menu are:

Type of Data

- Selection of Failure Events [FE] or Replacement Events [RE] determines which set of data will be used in the yearly summaries.

Overall and Yearly Data

- The [E]vents in each mission shows a table of the total number of events with a summary of Minimum, Maximum, Average and Standard Deviation.
- The [O]ccurrence of Events and Cumulative Frequency Distribution gives a table of the number of events, number of occurrences, and cumulative frequency distribution (CFD) tables.
- The [H]istogram of Event Occurrences & CFD (Figure 4) provides a plot of the data in the previous tables.

Probability of Needing a Replacement over the Mission Time

- The [P]OS to number of events will calculate the number of events that has at least the POS specified.
- The [N]umber of events to POS will give the Probability Of Sufficiency for a given number of events.

[C]umulative min/max estimates

- For a given round up fraction, the minimum, average and maximum events are tabulated.
- Cumulative data is calculated from the event histogram.

[A]ssistance

- A help screen is provided for guidance.

```
Renewal Simulation - V3.2 - Yearly Event Estimates


Type of Data:  (Currently  FE-failures)
  Failure Events          (FE)
  Replacement Events      (RE)

Overall and Yearly Data:
  [E]vents in each mission
  [O]ccurrence of Events and Cumulative Frequency Distribution (CFD)
  [H]istogram of Event Occurrences & CFD

  [P]OS to number of failure events
  [N]umber of failure events to POS

  [C]umulative min/max estimates

[A]ssistance

Selection:
```

Yearly Event Estimates Menu

```
Renewal Simulation - V3.2 - Occurrence of failure Events -  30 year Mission

No. of                              Cumulative
failure        No. of               failure
Events       Occurrences            Probability
------       -----------            -----------
 11            2                      0.0020
 12            2                      0.0040
 13            13                     0.0170
 14            42                     0.0590
 15            66                     0.1250
 16            141                    0.2660
 17            173                    0.4390
 18            185                    0.6240
 19            157                    0.7810
 20            90                     0.8710
 21            65                     0.9360
 22            39                     0.9750
 23            17                     0.9920
 24            7                      0.9990
 25            0                      0.9990
 26            1                      1.0000
              -----
```

Occurrence of failure Events Screen

## 3.5 Batch Files

This option is selected with the [B]atch & Summary File *{Main Menu}* selection. A list of ORU files may be submitted for consecutive execution using a RENEW batch file. This batch file contains the file names of individual ORU data files. The batch file is an ASCII text file and is given an .RB3 extension. The *Batch & Summary File* menu provides selections for creation, listing and use of batch files with the following commands:

[C]reate
: This selection is used to create a batch file (.RB3). The batch file may also be created or edited with a text processor.

[L]ist Contents
: The presence of the individual ORU data files (.RD3) listed in the batch file (.RB3) is checked. It is recommended that this selection be used prior to a batch run to ensure that all of the ORU data files are present.

[R]un
: The different ORUs are run in sequence with the results stored in the ORU data files (.RD3) for later retrieval.

[S]ummary of data & results (.RS3)
: Selected results from the ORU files are extracted and combined in a listing.

[SE]-03 Format
: Another selection of results from ORU files, printed in a 120 character wide text file. The file name has a .RE3 extension. This can be viewed with the [FV] *{Main Menu}* selection. (Note: SE-03 refers to a data requirement report for SSFP).

[B]lock Data Change
: The value of a single R&M data element is modified in all files listed in the batch file. This is done by selecting a [B]atch file *{Block Data Change}* and then the data [E]lement to change *{Block Data Change}* and the new value. The files will be modified on selecting [C]hange element value in files *{Block Data Change}*.

## 3.6 Saving & Retrieving Data Files

Using [S]ave Input Data and Results *{Main Menu}* will save the data and results to a file. The ORU name supplied in the data file is used to create the DOS file name with a .RD3 file extension. The user may change the name of the file before it is saved.

```
Renewal Simulation - V3.2 - Batch & Summary Files


Batch Files (.RB3):
  [C]reate Batch File
  [L]ist Batch File Contents
  [B]lock Data Change
  [R]un Batch

Summary Files:
  [S]ummary of Data & Results (.RS3)
  [V]iew Summary File Contents

  [SE] - 03 Format File (.RE3)

[H]elp

Selection:
```

Batch and Summary Files Menu

All files are saved and retrieved to/from the default DOS directory. This directory can be changed using Change Directory [CD] *{Main Menu}*.

[F]ile Data Input *{Main Menu}* can be used to locate and load data files in the default directory on the drive.

All of the RENEW results files are in text format and can be viewed using the File Viewer [FV] *{Main Menu}*.

## 4.0 RENEW MODEL BACKGROUND

### 4.1 Maintenance Interval Estimation

Preliminary maintenance analyses generally use the steady state average of the failure interval, represented by the MTBF, to calculate the number of maintenance events. Each failure is assumed to generate a maintenance action. Both Logistics [Blanchard, p.52] and Reliability use this approach. The number of failures over a given mission time is:

1) $n(t) = N * ( t / MTBF ) = N\lambda t$

where $n(t)$ = Number of failures
$N$ = Number of items
$\lambda$ = Failure rate
$t$ = Mission time

Maintenance repair hours and resupply quantity are then calculated from the number of failures and the Mean Time To Repair (MTTR).

2) Maintenance Hours = MTTR * n(t)

3) Resupply Quantity = n(t)

This approach is a good estimator under the following constraints:

- o Items exhibit only random failures
- o There is no internal redundancy
- o Mission times are long with respect to the MTBF
- o Repair is made with no downtime
- o Spares are always available
- o Every failure requires a spare
- o The MTTR is the same for every failure of a specific ORU

## 4.2 Renewal Approach

Steady state methods are appropriate when the mission time is many multiples of the basic Mean Time To Failure (MTTF) [Lewis, p.109]. Calculations based on steady-state averages will always over estimate the number of maintenance events by predicting extra events that do not occur [Barlow/Proschan, p. 53]. This error is caused by two factors:

### Fractional Carryover from End Effects

Averaging methods estimate the number of events from the number of MTBF intervals that occur over the mission life. Fractional events are counted as part of the average and increase the number of events. When many multiples of the MTBF occur during the mission time, the error from a fractional event is not significant in the total count. When the mission time approaches infinity the results reduce to the steady state [Lloyd/Lipow, p.275].

### MTBF and Wearout Interactions

The random and wearout failure modes are not independent. A random failure will preclude a wearout failure. The replacement ORU is thus "brand new" with its wearout life clock reset to zero. This is not accounted by either a a series R(t) function or a steady-state average.

The basic renewal theory equation directly calculates the number of renewals, M(t) [Barlow/Proschan, p.50]:

4) $$M(t) = F(t) + \sum_{k=1}^{Inf} \int_0^t F^{(k)}(t-x)\, dF(x)$$

where, $F(t) = 1 - R(t)$
$F^{(k)}$ = kth convolution of F(t)

Solution of equation 4) requires use of Laplace transforms. As an alternative to this, a computer-based simulation can be used. Interactions of the failure events with the mission time can be evaluated as they occur in the simulation. A simulation also allows other time varying factors to be included thus increasing the fidelity of the results, such as:

- o Staged deployment or assembly sequence
- o Early life failures
- o Technology improvement
- o Shuttle resupply intervals
- o Maintenance backlogs
- o Grouping of repairs

A simulation allows collection of year by year estimates of maintenance events while considering other factors. It also gives a more realistic assessment of events for a given set of data.

RENEW was written to perform a computer simulation that accounts for these interactions. The maintenance demand for a single type of ORU is generated. Renewal effect, early, random and limited life distributions, and staged deployment are accounted in the simulation. A Mean Time Between Demand (MTBD) for maintenance and a time dependent maintenance demand curve is generated. The simulation uses the following type of data to arrive at these final metrics for a type of ORU:

| | |
|---|---|
| ORU | Quantity and Time of deployment |
| | Early life probability and distribution |
| | Random event MTBF |
| | Wearout mean life and distribution |
| | K-Factor and reliability growth factors |
| | Replacement ratio |

| | |
|---|---|
| ENVIRONMENT | Mission time<br>Replacement Downtime |
| SIMULATION | Number of trials<br>Divisions per year |

The primary product of RENEW is an average failure event time histogram derived from the simulation of maintenance events (Figure 3). The horizontal axis is the mission timeline and the vertical axis is the number of events. This failure histogram gives an estimate of the year by year demand. The MTBD for all ORUs and the Mean Time Between Maintenance (MTBM) for an individual ORU are obtained from the total number of events and downtime over the simulated mission time.

## 4.3 Failure Simulation

RENEW uses a Monte Carlo event stepped simulation. The event time generation uses a modified approach to account for the combination of the three major distributions (early, random and wearout). With competing risk models [Mann, p. 142], the reliability functions are multiplied:

5) $R_{oru} = R_{early} * R_{random} * R_{wearout}$

When this is used for all three distributions, the early life reliability ($R_{early}$) typically dominates the ORU reliability because it precludes any random or wearout failures. This model is, instead, used with the early failure distribution removed and applied to random and wearout events in a mixed distribution.

Early failures due to infant mortality, usually within about 12 months, will only occur on a percentage of the ORUs. To overcome the problem with equation 5) and more accurately depict expected behavior, a mixed distribution model [Mann, p. 138] is used to depict the early life failures. This model uses an early failure probability (EP) of occurrence. The simulation thus activates early failures with this probability. When no early failure occurs, a competing risk model is used for estimating only the random and wearout failure events. This modified approach is shown below:

6) $$R_{oru} = \begin{cases} R_{early} & \text{with probability EP} \\ R_{random} * R_{wearout} & \text{with probability 1-EP} \end{cases}$$

Time to failure intervals for ORUs are generated using algorithms derived from the reliability equation, R(t), for each failure distribution. R(t) is solved for time, t, with reliability, R(t), replaced by the random number. This generates a time to next failure that is governed by the distribution. The simulation steps in time from one failure of an ORU to the next. Appendix C lists the equations used for failure times with each failure distribution. See Figure 6 for use of these parameters in failure time calculation. The input values are discussed below:

Early Life

Three parameters determine early life failures. The early life probability of occurrence (EP) factor (range of 0 to 1) determines the occurrence of early life failures. Each time an ORU is checked for next failure time, a random number is compared with EP. If the random number is smaller than EP then only the early life weibull distribution is used. Otherwise, the simulation determines the next failure from the random and wearout distributions.

Random & Wearout Events

The MTBF of the ORU determines the next random failure event time while the wearout mean life and shape determines the next wearout failure event time. These two event times are compared. The earliest time is considered the next failure event. The other, later, time is discarded.

K-factors

K factors are a means to account for extra maintenance actions that are not part of the random and wearout failure estimates. The MTBF and mean wearout life are modified by the K-factor as shown in Appendix C. The early life distribution is not affected by the K-factors.

Early Life/Reliability Growth Factors

These factors are used to account for early life and technology improvement of the ORUs. These factors are combined with the K-factor by multiplication and then used to modify the ORU mean life. Three factors with decreasing values are generally used. The first failure time of an ORU during a mission is modified by the first factor. The second failure time by the second factor and the third and subsequent failures by the third factor. This improves the failure rate of the ORU with subsequent replacement. It is based on the assumption that improvements are made in the replacement ORUs that reduce the failure rate of the ORU. While the approach was developed to model early failures it is more useful in accounting for reliability growth.

Replacement Downtime

The simulation uses this value as an average time before a replacement for the failed ORU is delivered to the site and ready for replacement. This time period is added to the MTTR to determine when the new ORU will start operation. Since the simulation only estimates a single ORU, interactive effects from grouping of repairs, and backlogs are not modeled.

## 4.4 Variable Failure Rates

Both random and wearout failure distributions can be modeled with a time varying mean value. This feature was added to more accurately depict situations where the equipment experiences different environmental/operational conditions. The effect of these varying conditions is usually depicted in a single time-averaged duty cycle factor. In a discrete event simulation, like RENEW, it is possible to represent the timing of the expected conditions and represent the changes in MTBF and mean life as a direct result of the changing conditions.

The data entry consist first of the number of segments, then the MTBF or Mean Life parameter value and the end of the mission based time segment for which this value applies. These values are entered initially through [K]eyboard entry *{Main Menu}* or later using the *List/Change Parameters* menu.

The modeling approach for variable MTBF and variable Mean Life, although similar, are treated differently in the simluation. For random distributions, the algorithm does not have to track the effect of the previous operation because of the "memoryless" characteristic of a random distribution. However, calculations using the wearout distribution require tracking the effect of previous time periods on shortening of the equipment life.

### 4.4.1 Variable Random Failure Rate

The algorithm is shown in Figure 7. The MTBF for the first time period is determined. The exponential distribution is then used to calculate the time to failure ($TTF_i$) as shown in Appendix C. This $TTF_i$ plus the offset from the previous period is compared to the next time period, $t_{i+1}$. If the equipment survives past the next period then another $TTF_i$ is calculated using the next MTBF. This process repeats until a $TTF_i$ is less than the next period, $t_{i+1}$.

## 4.4.2 Variable Mean Wearout Life

The Time to Failure algorithm for variable mean life using a Weibull distribution is depicted in Figure 8. This algorithm will calculate a wearout time given a time varying (in segments) mean life.

Failure times are calculated for each segment that take into account the previous wear on the equipment. This "memory" of previous environments is factored into the calculation. First, a single random number is used for all time segments since a single event is being calculated from a composite function of all the wearout distributions across all the time segments of the mission. Second, an offset is calculated to account for the wear in the previous time segments.

The process repeats until the equipment failures before the end of a segment. If the equipment survives into the last segment, it will fail during this segment since the failure time will be less than infinity (inf).

An example of the simulation calculations is shown in Appendix G using the parameters in Figure 8. The given values are a Weibull shape of 3, a single random number of 0.786 for this single time to failure calculation, and an ORU activation at t=0. The given values for variable mean life ($\mu_i$) are shown for each segment (i). For example, mean life is 10 years from the 3rd to 4th year of the mission. The Simulation Example lists the changing parameter values as the loop in Appendix G is executed until the wearout time to fail is determined. Initial values are shown under i=0. The parameter $t_b$ accounts for any delayed activation of the ORU. It is set to zero since the ORU is activated at the start of the mission. $R_{end}$ is 1.0 assuming the ORU is new. For i=1, the mean life, is selected and the characteristic life ($\theta_i$) is calculated from Appendix C equation 1). A time to fail, $TTF_i$, is calculated solely from the characteristic life and the "single" random number. $TTF_i$ is then adjusted for previous wear using $t_s$ and then to the mission timeline using $t_b$. The time $t_s$ is calculated using the reliability at the end of the previous segment, $R_{end}$. The time $t_b$ tracks the end of the last segment in mission time. The resulting $TTF_w$ is then compared to the end of the segment, $t_{i+1}$. For i=1, Since 4.18 is greater than 3 years, the ORU has survived this segment. An equivalent operating time is calculated for the end of the segment, $t_{end}$, using the start time offset, $t_s$, and the segment duration, ($t_{i+1}$ - $t_i$). This time is used to calculate the reliability at the end of this segment, $R_{end}$. The process repeats with retrieval of the next segment mean life and recalculation of the parameters until a failure time, $TTF_w$, is less than the end of a time segment. In this example, the ORU survives into the last segment with 5.16 years returned as the wearout failure time.

## 4.5 K-Factors & Removal Ratios

Experience has shown that the number of maintenance actions are generally higher than the number of confirmed failures [RAMS, 1988, p.102]. These extra maintenance actions include both replacement of ORUs and non-replacement actions (e.g. adjustments, no fault found). To account for this discrepancy, K-factors have been developed to estimate the increased number of maintenance events. An approach for quantifying these values using field data has been developed by the External Maintenance Task Team [EMTT, Vol. I, Pt. 2, Sec. D-2] and re-evaluated by the External Maintenance Solutions Team [EMST]. The K-factors were developed to depict the increased maintenance due to the type of ORU. Six ORU equipment types were defined. These factors translate the MTTF value into a Mean Time Between Maintenance Actions (MTBMA):

7) $$K = \frac{\text{\# Maintenance Actions}}{\text{\# Confirmed Failures}} = \frac{\text{MTTF}}{\text{MTBMA}}$$

LeRC has been using a removal ratio (range of 0 to 1) to adjust the MTBMA for maintenance actions that do not require a spare ORU. This converts the MTBMA to a Mean Replacement Interval (MRI):

8) $$\text{Removal Ratio} = \frac{\text{\# Replacements}}{\text{\# Maintenance Actions}} = \frac{\text{MTBMA}}{\text{MRI}}$$

## 4.6 Resource Estimation

Mean maintenance crew-hours/year (MMH/year) and resupply quantity are calculated from the results of the RENEW simulation. The Maintenance Action Rate (MAR) gives the rate of maintenance event occurrence for all ORUs of a particular type.

9) $$\text{MAR} = \text{\# of ORUs} * \text{\# of failure events/year} = 1 / \text{MTBD}$$

The MMH/year is calculated from the Mean Time to Repair (MTTR) and the MAR:

10) $$\text{MMH/year} = \text{MTTR} * \text{MAR} * \text{\# of Crew}$$

An overall Spares Launch Rate (SLR) is calculated from the quantity of ORUs and the MRI:

11) $$\text{SLR} = \frac{\text{\# of ORUs}}{\text{MRI}} = \text{MAR} * \text{RR}$$

The annual resupply mass results from the SLR and mass of an ORU:

12) Resupply Mass/year = ORU Mass * SLR

The process of calculating MMH/year and annual resupply mass using equations 8) to 12) is shown in Figure 9.

## 4.7 Results

Both average and time-varying results are available from the simulation. The following averages of the simulation are calculated:

MTBD

The Mean Time Between Demand (MTBD) for maintenance is an average derived from the mission time and the total number of ORU maintenance events. It is based on the mission time and not the operating time of the ORU. The MTBD is a composite value that accounts for the total quantity and deployment schedule of a type of ORU on orbit.

MTBM

The Mean Time Between Maintenance (MTBM) is an average of the number of ORU operating hours between maintenance events. This value is for a single ORU.

Percent failure type contribution

The percent of each type of failure (early, random, wearout) is calculated from a tally of the total number of failures and each failure type.

## 4.8 Assumptions

No prediction is complete without a list of the assumptions used to calculate the results. The following is a summary of the assumptions used by RENEW.

- Only ORU level items fail and get repaired
- ORU restored to good-as-new condition
- An average resupply interval is used for each failure
- ORU failures can be modeled with the combined Early Life, Random and Weibull distributions
- There are no interactions between ORUs during maintenance; each ORU is repaired independently
- Random and wearout events are independent
- There is no ORU internal redundancy
- Repair queues are not modeled
- Downtime effects from shuttle resupply intervals, maintenance backlogs, and grouping of repairs are estimated with a single downtime parameter
- A sufficient number of trials have been run to give the necessary accuracy
- K-factor used on both random and wearout
- K-factors accurately represent increased maintenance for each ORU based on its type
- The same K-factors apply to both random and wearout events
- Downtime is a single average value and does not consider:
    - On-orbit sparing
    - Deferred maintenance
    - Variable MTTR
- The repair ratio is not applied in the simulation
- K-factors only apply to MTBF and wearout life but not MTBFmmd
- The system will not be repaired after the end of the defined mission time
- The results are only as accurate as the assumptions

# APPENDIX A - INPUT DATA DESCRIPTIONS

## KEYBOARD DATA ENTRY

The following data items are requested during [K]eyboard data input *{Main Menu}*. The valid input values are shown in parenthesis (). Values may be changed from the *{List/Change Parameters Menu}* after keyboard data entry.

<u>ORU Abbreviation/Name</u>
This name may be any length. However, the first 8 characters must be unique since this is used to create the DOS data file name.

<u>Reliability Type (EL, EC, ST, SM, EM, ME)</u>
This assignment controls which default K-factor is selected for the ORU. The list of default K-factor values can be viewed and changed from the [C]onstants selection *{Main Menu}*. The default K-factor assigned to an ORU may be changed in the [L]ist/Change Parameters selection *{Main Menu}*.

<u>No. of ORUs (>0)</u>
This indicates the number of ORUs that will be simulated. Start times will be requested for each of these ORUs.

<u>Early Failure Probability (0 to 1)</u>
This parameter determines the chance of an early failure occurrence. The early failure model is removed from the simulation if this parameter is set to 0.

<u>Mean Early Life (>0)</u>
This parameter is used if the probability of early failure is not 0. The early failure model is a Weibull distribution with a decreasing hazard rate (shape < 1). This value sets the mean life of the model.

<u>Early Life Weibull Shape (0 to 1)</u>
This parameter is used if the probability of early failure is not 0. The shape must be less than 1 since the early failure model must have a decreasing hazard rate.

<u>MTBF Type (V, C)</u>
This selection determines whether there is a single (C-Constant) or multiple (V-Variable) MTBF values over the mission time.

Number of MTBF Periods
This appears if a variable MTBF Type is selected. The value indicates how many MTBF values will be modeled over the mission time.

MTBF (>0)
The Mean Time Between Failures (MTBF) represents the chance of random failure during the mission.

Duty Cycle (0 to 1)
This factor is directly applied to the MTBF to account for the ratio of ORU operating time to total time. Non-operating time is assumed to have an infinite MTBF.

MTBF-Micrometeroid/Debris (>0)
This parameter accounts for the random occurrence of a failure caused by a micrometeroid or debris strike. This is separated from the MTBF for tracking proposes and other factor application. The K-factor and duty cycle is applied to the MTBF first. The result is then combined with the MTBF-Micrometeroid/Debris for determination of event times. Set this value to 1E+29 to remove it from the simulation.

Wearout Mean Life Type (V, C)
This selection determines whether there is a single (C-Constant) or multiple (V-Variable) Wearout Mean Life values over the mission time. The Weibull Failure Free Period is set to 0 when variable mean life is used. A single Weibull Shape Factor is applied to the mean life in all time segments.

Number of Mean Life Periods
This appears if a variable Mean Life Type is selected. The value indicates how many mean life values will be modeled over the mission time.

Wearout Weibull Mean Life (>0)
This is the mean life, $\mu$, of the Weibull wearout distribution. The mean life parameter is converted to characteristic life for time to failure calculations. See Appendix C, equation 1).

Wearout Weibull Failure Free Period (>=0)
This is the time period over which no wearout failures can occur. It is the location parameter of the Weibull distribution, $\gamma$.

Wearout Weibull Shape Factor (>1)
This is the shape parameter, $\beta$, of the Weibull wearout distribution.

Replacement Downtime (>=0)
This parameter is the average time to obtain a replacement ORU. It is used to sumulate the logistics delay time. The total downtime is the sum of this parameter and the MTTR for the ORU.

Mission Time (>0)
This is set to the length of one mission in years. Failures will be repeatedly simulated up to this end of mission time.

No. Divisions/year (>=1)
This sets the number of event divisions per year for collection of histogram data. More simulations are needed to obtain good data as the number of divisions are increased. It is usually set to 1 for collection of failures over one year intervals. A value of 4 would collect failures over 3 month intervals.

Number of Simulations (>=1)
This is the number of simulations of each mission time that will be performed by RENEW. At least 100 simulations should be run to in order to depict the maintenance event pattern.

Replacement Ratio (0 to 1)
This is an average value representing the percentage of times that an ORU will be replaced once a failure event occurs. A value of 1 means that a replacement spare will be required for all failures. A value of 0 means failures are repaired without the need for a spare. This difference is reflected in the downtime and failure/replacement event calculations.

ORU Start Times (>=0)
This is the start time, using the mission time clock, for each ORU. This allows for staged deployment. A value of 5 indicates that the ORU is not present until 5 years into the mission. To depict standby failures before activation, the variable MTBF or variable life parameters should be used.

# APPENDIX B - PROGRAM INSTALLATION AND DATA FILES

## PROGRAM INSTALLATION

There is only a single program file that is needed to run RENEW. The file "RENEW32.EXE" should be copied to the directory where the data files will be stored. The program can be run from a floppy or hard disk system. To run the program, type "RENEW32" from the DOS prompt. The main menu screen will be displayed. A sample set of data and results files is provided on the disk with the base file name "ORU".

## DATA FILES

The following data files are generated by RENEW:

| File Extension | Description |
|---|---|
| .RD3 | ORU Data File<br>This is the basic ORU data file. It contains both input data as well as results. Combining both input and results ensures traceability of results to input data. The file may contain only input data if the simulation was not executed when the data was saved. Once results have been generated, this file will contain the input data followed by the results. |
| .RB3 | Batch file<br>This is and ASCII file that contains a listing of individual ORU file names. The file names, with the .RD3 file extension, are left justified with no drive or directory attached. RENEW will only use files in the current default directory. |
| .RS3 | RENEW Summary File<br>This is an 80 column report of selected input data and results. This is generated from the *Batch And Summary Files Menu*. |
| .RE3 | RENEW SE-03 report<br>This report is a 132 character wide report of selected input data and results. It is generated from the *Batch And Summary Files Menu*. |

## APPENDIX C - EQUATIONS USED IN RENEW

Characteristic Life ($\theta$) is calculated from the Mean Life ($\mu$), Failure Free period ($\gamma$) and Shape ($\beta$) using the gamma function [Lewis, p. 97]:

1) $$\theta = \frac{\mu - \gamma}{\Gamma [ 1 + (1/\beta) ]}$$

Early life failures are modeled using a weibull distribution with a mean life ($\mu_e$) a shape factor ($\beta_e$) less than 1, and a random number (R) substituted for the Reliability to obtain the time to fail ($TTF_e$):

2) $$TTF_e = \frac{\mu_e}{\Gamma [ 1 + (1/\beta_e) ]} [ -\ln(R) ]^{(1/\beta e)}$$

For the wearout distributions, the K-factor is applied as a multiplier to the hazard rate, h(t). An effective characteristic life ($\theta'$) with K-factor effects is calculated:

3) $$h(t) = \frac{K \; \beta \; t^{\beta-1}}{\theta^{\beta}} = \frac{\beta \; t^{\beta-1}}{(\theta')^{\beta}}$$

4) $$\text{where, } \theta' = \frac{\theta}{K^{(1/\beta)}}$$

A Time To Failure ($TTF_w$) for the weibull wearout distribution is calculated from the Characteristic Life ($\theta$), K-Factor (K), and Shape ($\beta$):

5) $$TTF_w = \frac{\theta}{K^{(1/\beta)}} [ -\ln(R) ]^{(1/\beta)}$$

6) $$TTF_w = \frac{\mu}{\Gamma [ 1 + (1/\beta) ] \; K^{(1/\beta)}} [ -\ln(R) ]^{(1/\beta)}$$

A Time To Failure for the exponential ($TTF_r$) distribution is calculated from the MTBF, K-factor (K) and a random number (R) substituted for the reliability:

7) $$TTF_r = - \ln(R) * \frac{MTBF}{K}$$

# APPENDIX D - ABBREVIATIONS AND SYMBOLS

## Abbreviations/Acronyms

| | |
|---|---|
| CFD | Cumulative Frequency Distribution |
| DOS | Disk Operating System |
| EVA | Extravehicular Activity |
| IVA | Intravehicular Activity |
| LeRC | NASA Lewis Research Center |
| LDT | Logistics Downtime |
| MAR | Maintenance Action Rate |
| MMD | Micrometeroid Debris |
| MRI | Mean Replacement Interval |
| MTBF | Mean Time Between Failure |
| MTBFE | Mean Time Between Failure Event |
| MTBD | Mean Time Between Demand |
| MTBMA | Mean Time Between Maintenance Action |
| MTTF | Mean Time To Failure |
| MTTR | Mean Time To Repair |
| ORU | Orbital Replacement Unit |
| pdf | Probability Density Function |
| POS | Probability of Sufficiency |
| ROB | Robotic |
| RR | Removal Ratio |
| R&M | Reliabillity & Maintainability |
| SLR | Spares Launch Rate |
| SSFP | Space Station Freedom Program |
| TTF | Time To Failure |
| WP-04 | Work Package 4, Space Station Freedom Program |

## Symbols

| | |
|---|---|
| $\beta$ | Weibull shape parameter (beta) |
| $\Gamma(x)$ | Gamma function |
| $\gamma$ | Weibull failure free period |
| $h(t)$ | Hazard rate function |
| $\lambda$ | Failure rate |
| $\mu$ | Mean life |
| $R(t)$ | Reliability function |
| $\theta$ | Weibull characteristic life |

# APPENDIX E - BIBLIOGRAPHY

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# APPENDIX F - SAMPLE RENEW DATA FILE

## DATA FILE: ORU1.RD3

```
Renewal Simulation_V                    3.2
Simulation_Run_Date                     10-27-1992
ORU_Name                                ORU_1
ORU_Type                                EL
No._of_ORUs                              6
Prob._of_Early_Failure                   .05
Early_Mean_Life_(years)                  1
Early_Shape                              .4
Variable/Constant MTBF                  C
MTBF_(years)                             35
MTBF_Micrometeroid_(years)               1E+29
Variable/Constant Life                  C
Wearout_Mean_Life_(years)                15
Wearout_Failure_Free_Period_(years)      0
Wearout_Shape                            10
Replacement_Downtime_(years)             0
Number_of_Simulations                    1000
Mission_Time_(years)                     30
Bins_per_year                            1
Rel_Growth_Factor_1                      3.3
Rel_Growth_Factor_2                      2.17
Rel_Growth_Factor_3                      .6666667
K-factor                                 1.63
ORU_Mass                                 30
EVA_MTTR                                 .6
Robotic_MTTR                             0
IVA_MTTR                                 0
Replacement_Ratio                        .8
No._EVA_Crew                             1
No._IVA_Crew                             0
Null_Data                                1
Null_Data                                1
ORU_#                                   Start_Time_year
 1                                       0
 2                                       0
 3                                       1.5
 4                                       1.5
 5                                       4
 6                                       4
Total_Failures/Mission                   17.911
Std_Dev                                  2.227564
Average_Failures/year                    .5970333
Max_Failures_year                        5
Max_No._Failures                         .861
Percent_Early                            6.214058
Percent_Random                           67.98057
Percent_Wearout                          25.80537
Total_No._Maintenance_Actions            17.911
Total_No._Replacements                   14.353
Std_Dev                                  2.443022
Total_Available_Time                     169
Total_Downtime_(years)                   1.226781E-03
MTBFE_(years)                            1.674948
ORU_MTBFE_(years)                        9.435474
Mean_Annual_Resupply_Mass_(lbs)          14.3288
EVA_MMH/yr                               .35822
Robotic_MMH/yr                           0
IVA_MMH/yr                               0
Time          #_Failures     #_Early        #_Random       #_Wearout
 1              .368           .08            .288           0
 2              .506           .088           .418           0
 3              .551           .04            .511           0
 4              .564           .029           .535           0
 5              .861           .103           .758           0
 6              .727           .035           .691           .001
 7              .728           .047           .681           0
 8              .684           .04            .643           .001
 9              .691           .05            .639           .002
 10             .571           .02            .539           .012
 11             .564           .028           .523           .013
```

| | | | | |
|---|---|---|---|---|
| 12 | .614 | .027 | .551 | .036 |
| 13 | .623 | .033 | .515 | .075 |
| 14 | .639 | .028 | .484 | .127 |
| 15 | .633 | .032 | .438 | .163 |
| 16 | .66 | .028 | .4 | .232 |
| 17 | .628 | .026 | .338 | .264 |
| 18 | .62 | .04 | .336 | .244 |
| 19 | .644 | .036 | .287 | .321 |
| 20 | .639 | .035 | .305 | .299 |
| 21 | .585 | .035 | .27 | .28 |
| 22 | .564 | .032 | .261 | .271 |
| 23 | .545 | .025 | .266 | .254 |
| 24 | .578 | .03 | .253 | .295 |
| 25 | .532 | .029 | .228 | .275 |
| 26 | .532 | .026 | .249 | .257 |
| 27 | .478 | .025 | .194 | .259 |
| 28 | .545 | .024 | .21 | .311 |
| 29 | .507 | .024 | .178 | .305 |
| 30 | .53 | .018 | .187 | .325 |

| | |
|---|---|
| Min_Failure_Events | 11 |
| Max_Failure_Events | 26 |
| Min_Replacement_Events | 6 |
| Max_Replacement_Events | 22 |

Failure_Occurrence_Histogram

| | | |
|---|---|---|
| 11 | 2 | 0.0020 |
| 12 | 2 | 0.0040 |
| 13 | 13 | 0.0170 |
| 14 | 42 | 0.0590 |
| 15 | 66 | 0.1250 |
| 16 | 141 | 0.2660 |
| 17 | 173 | 0.4390 |
| 18 | 185 | 0.6240 |
| 19 | 157 | 0.7810 |
| 20 | 90 | 0.8710 |
| 21 | 65 | 0.9360 |
| 22 | 39 | 0.9750 |
| 23 | 17 | 0.9920 |
| 24 | 7 | 0.9990 |
| 25 | 0 | 0.9990 |
| 26 | 1 | 1.0000 |

Replacement_Occurrence_Histogram

| | | |
|---|---|---|
| 6 | 1 | 0.0010 |
| 7 | 4 | 0.0050 |
| 8 | 3 | 0.0080 |
| 9 | 11 | 0.0190 |
| 10 | 31 | 0.0500 |
| 11 | 59 | 0.1090 |
| 12 | 123 | 0.2320 |
| 13 | 140 | 0.3720 |
| 14 | 155 | 0.5270 |
| 15 | 156 | 0.6830 |
| 16 | 126 | 0.8090 |
| 17 | 98 | 0.9070 |
| 18 | 47 | 0.9540 |
| 19 | 27 | 0.9810 |
| 20 | 10 | 0.9910 |
| 21 | 8 | 0.9990 |
| 22 | 1 | 1.0000 |

Year_by_Year_Histogram_Data

| | |
|---|---|
| Max_Failure_Occurrences | 386 |
| Max_Failure_Events | 5 |
| Max_Replacement_Occurrences | 375 |
| Max_Replacement_Events | 5 |

Year 1 Failures

| | | | | | |
|---|---|---|---|---|---|
| 684 | 268 | 44 | 4 | 0 | 0 |

Year 1 Replacements

| | | | | | |
|---|---|---|---|---|---|
| 737 | 236 | 25 | 2 | 0 | 0 |

Year 2 Failures

| | | | | | |
|---|---|---|---|---|---|
| 602 | 304 | 83 | 9 | 1 | 1 |

Year 2 Replacements

| | | | | | |
|---|---|---|---|---|---|
| 668 | 271 | 54 | 6 | 1 | 0 |

Year 3 Failures

| | | | | | |
|---|---|---|---|---|---|
| 577 | 315 | 90 | 16 | 2 | 0 |

Year 3 Replacements

| | | | | | |
|---|---|---|---|---|---|
| 643 | 279 | 67 | 9 | 2 | 0 |

Year 4 Failures

| | | | | | |
|---|---|---|---|---|---|
| 577 | 306 | 95 | 20 | 2 | 0 |

```
Year 4  Replacements
 635          291          66           8            0            0
Year 5  Failures
 405          386          161          39           9            0
Year 5  Replacements
 482          375          112          28           3            0
Year 6  Failures
 490          352          112          36           7            3
Year 6  Replacements
 562          324          93           16           2            3
Year 7  Failures
 477          364          123          28           6            2
Year 7  Replacements
 542          341          91           20           5            1
Year 8  Failures
 508          342          117          24           9            0
Year 8  Replacements
 577          316          88           18           1            0
Year 9  Failures
 503          343          122          24           8            0
Year 9  Replacements
 569          332          83           14           2            0
Year 10  Failures
 577          303          96           21           2            1
Year 10  Replacements
 640          270          75           12           2            1
Year 11  Failures
 578          305          96           17           4            0
Year 11  Replacements
 659          264          64           9            4            0
Year 12  Failures
 543          329          103          21           4            0
Year 12  Replacements
 625          287          73           13           2            0
Year 13  Failures
 546          320          109          18           4            3
Year 13  Replacements
 615          294          75           13           3            0
Year 14  Failures
 529          344          92           31           2            2
Year 14  Replacements
 602          306          73           18           1            0
Year 15  Failures
 547          313          108          25           6            1
Year 15  Replacements
 607          288          90           13           2            0
Year 16  Failures
 498          370          109          20           3            0
Year 16  Replacements
 572          337          77           12           2            0
Year 17  Failures
 526          348          100          24           2            0
Year 17  Replacements
 603          317          71           9            0            0
Year 18  Failures
 541          332          100          21           5            1
Year 18  Replacements
 601          308          71           16           3            1
Year 19  Failures
 520          353          98           21           8            0
Year 19  Replacements
 590          314          83           9            4            0
Year 20  Failures
 527          335          111          26           1            0
Year 20  Replacements
 607          297          80           16           0            0
Year 21  Failures
 570          304          101          21           4            0
Year 21  Replacements
 635          274          79           9            3            0
Year 22  Failures
 558          335          93           13           1            0
Year 22  Replacements
 625          303          65           7            0            0
Year 23  Failures
 581          314          86           17           2            0
Year 23  Replacements
```

| | | | | | |
|---|---|---|---|---|---|
| 645 | 289 | 55 | 10 | 1 | 0 |
| Year 24 Failures | | | | | |
| 576 | 301 | 98 | 20 | 4 | 1 |
| Year 24 Replacements | | | | | |
| 642 | 268 | 74 | 14 | 2 | 0 |
| Year 25 Failures | | | | | |
| 587 | 313 | 86 | 10 | 3 | 1 |
| Year 25 Replacements | | | | | |
| 643 | 291 | 58 | 7 | 0 | 1 |
| Year 26 Failures | | | | | |
| 590 | 317 | 69 | 20 | 3 | 1 |
| Year 26 Replacements | | | | | |
| 664 | 275 | 47 | 11 | 3 | 0 |
| Year 27 Failures | | | | | |
| 622 | 294 | 71 | 10 | 3 | 0 |
| Year 27 Replacements | | | | | |
| 694 | 250 | 48 | 8 | 0 | 0 |
| Year 28 Failures | | | | | |
| 575 | 329 | 76 | 16 | 4 | 0 |
| Year 28 Replacements | | | | | |
| 650 | 281 | 57 | 10 | 2 | 0 |
| Year 29 Failures | | | | | |
| 594 | 317 | 79 | 9 | 0 | 1 |
| Year 29 Replacements | | | | | |
| 657 | 278 | 60 | 5 | 0 | 0 |
| Year 30 Failures | | | | | |
| 591 | 304 | 92 | 10 | 3 | 0 |
| Year 30 Replacements | | | | | |
| 657 | 270 | 63 | 8 | 2 | 0 |

# APPENDIX G - VARIABLE MEAN LIFE EXAMPLE

Given Values:

Mean Life Weibull Shape (β) = 3
Random number (RND#) = .786
Start Time = 0

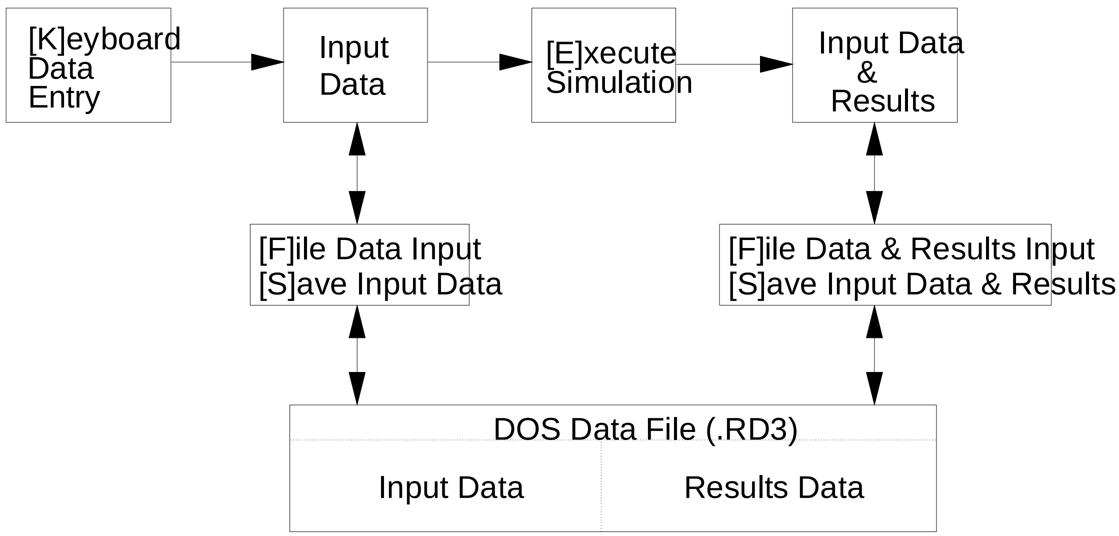
Variable Mean Life Data (years):

| Segment (i) | From | To | Mean Life |
|---|---|---|---|
| 1 | 0 | 3 | 6 |
| 2 | 3 | 4 | 10 |
| 3 | 4 | inf | 12 |

Simulation Example (refer to Figure 8):

| Parameter | Values | | | |
|---|---|---|---|---|
| i | 0 | 1 | 2 | 3 |
| $\mu_i$ | -- | 6 | 10 | 12 |
| $\theta_i$ | -- | 6.72 | 11.2 | 13.4 |
| $TTF_i$ | -- | 4.18 | 6.97 | 8.36 |
| $t_s$ | -- | 0 | 5 | 7.2 |
| $TTF_w$ | -- | 4.18 | 4.97 | 5.16 |
| $t_{i+1}$ | -- | 3 | 4 | inf |
| $t_i$ | -- | 0 | 3 | -- |
| $t_{end}$ | -- | 3 | 6 | -- |
| $t_b$ | 0 | 3 | 4 | -- |
| $R_{end}$ | 1.0 | .915 | .857 | -- |

FIGURE 1 - Data Entry/Retrieval Process




Note: [x] = Selection from Main Menu

FIGURE 2 - Composite Reliability Function Display

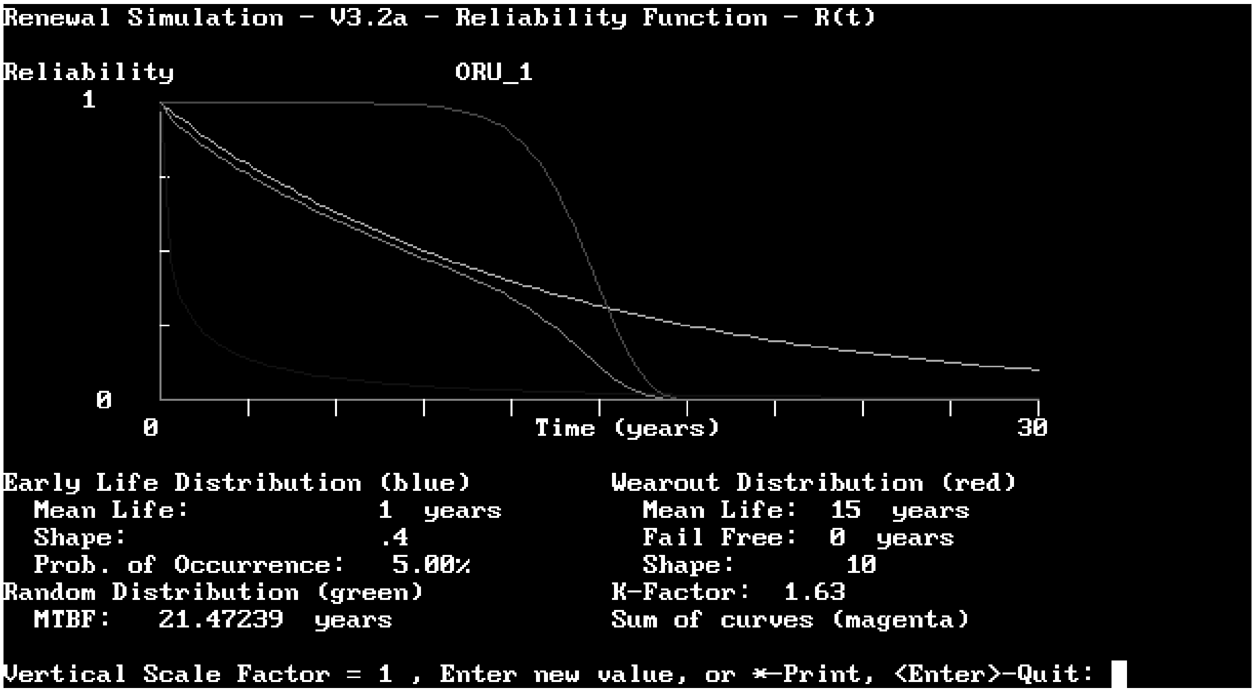



FIGURE 3 - Failure Event Histogram Plot

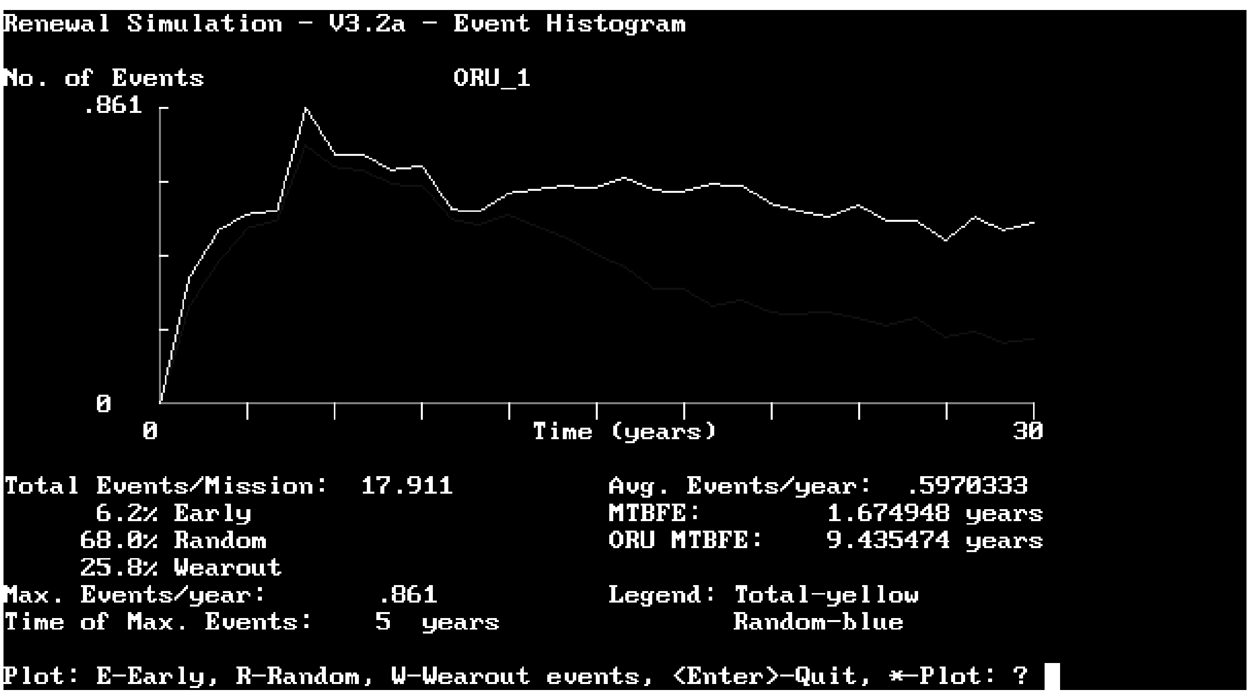


FIGURE 4 - Failure Occurrence Histogram

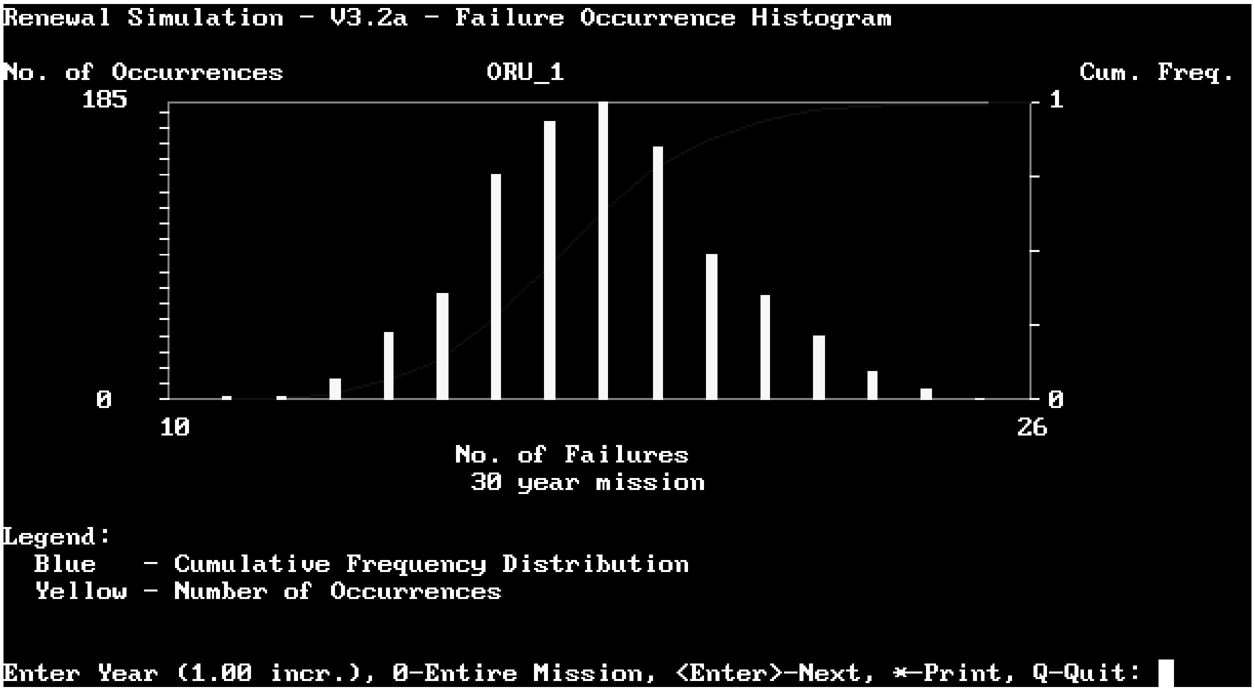


FIGURE 5 - Main Simulation Loop Flow Diagram

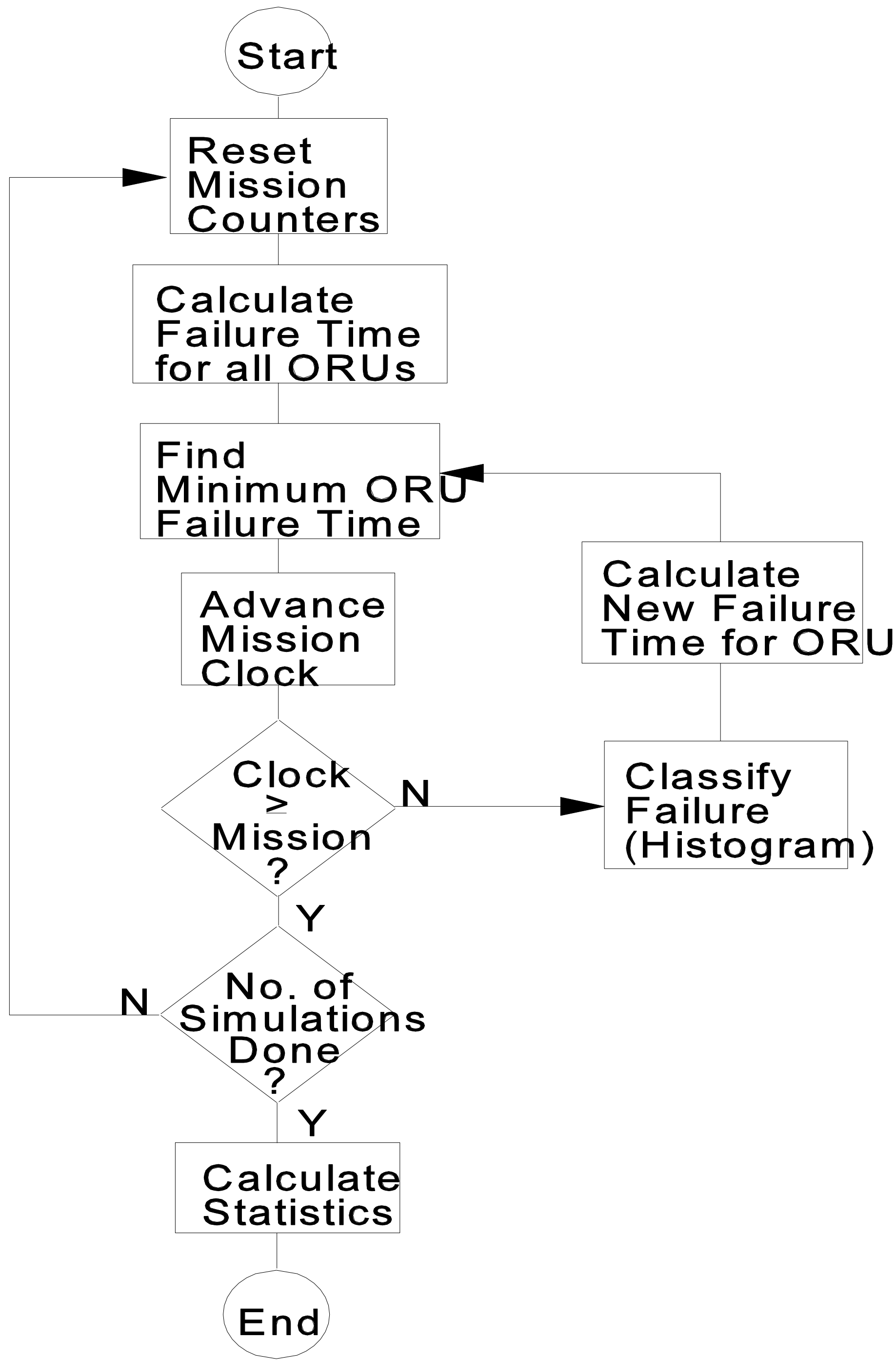


FIGURE 6 - Failure Time Calculation

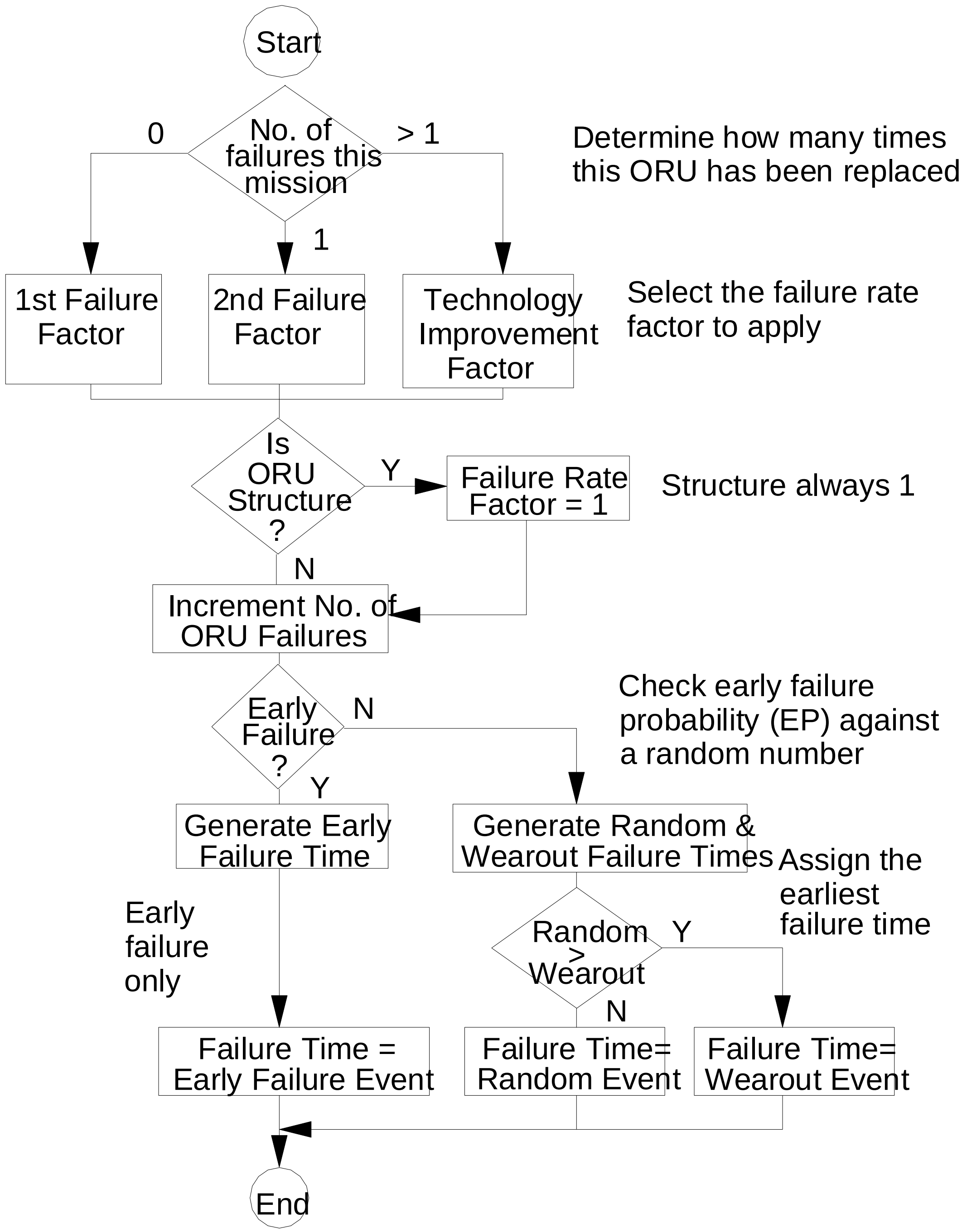
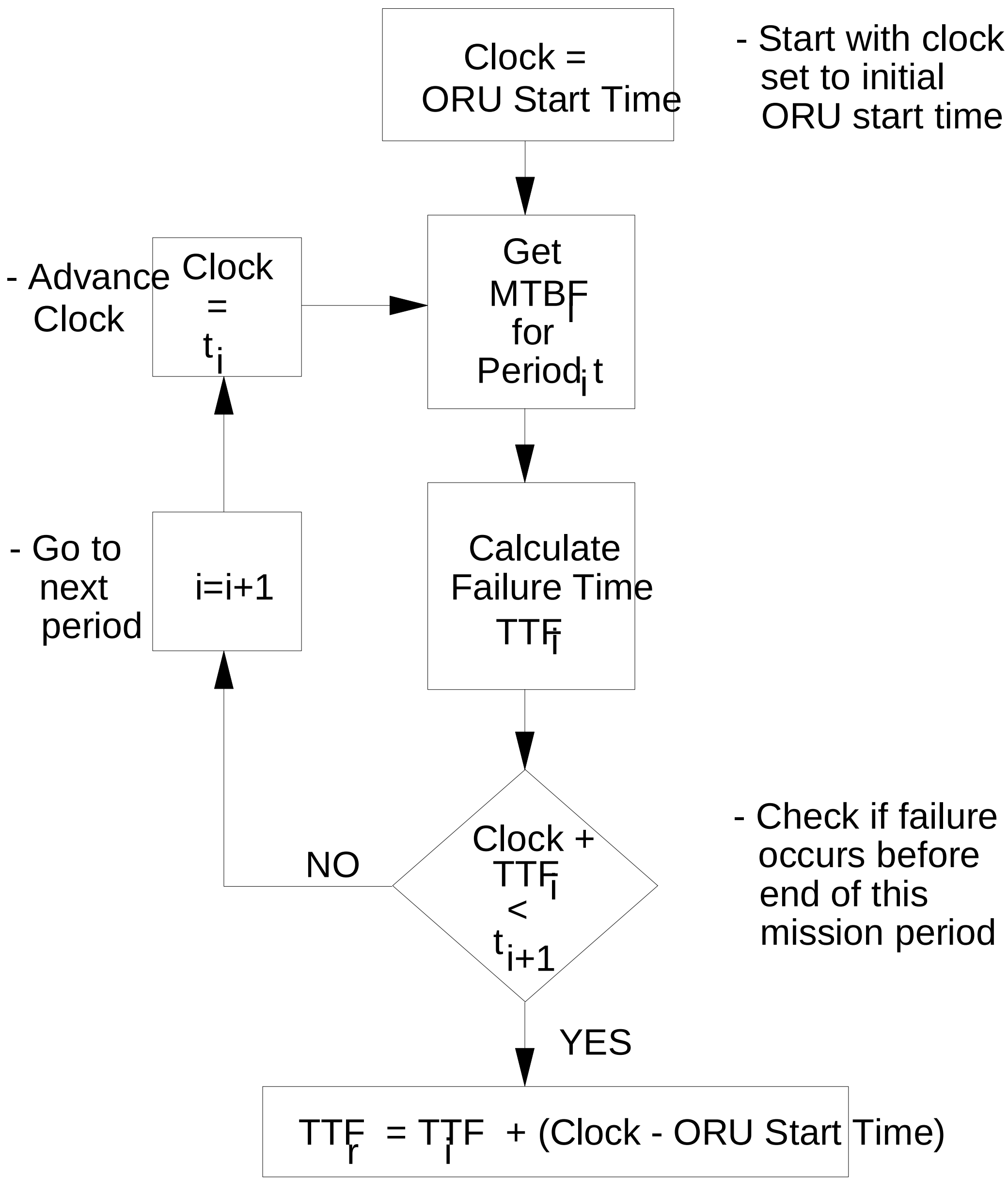


FIGURE 7 - Variable MTBF Flow Diagram




$TTF_i$ = Time to Fail using $MTBF_i$

$TTF_r$ = Time to Fail, random, for simulation

FIGURE 8 - Variable Mean Life Flow Diagram

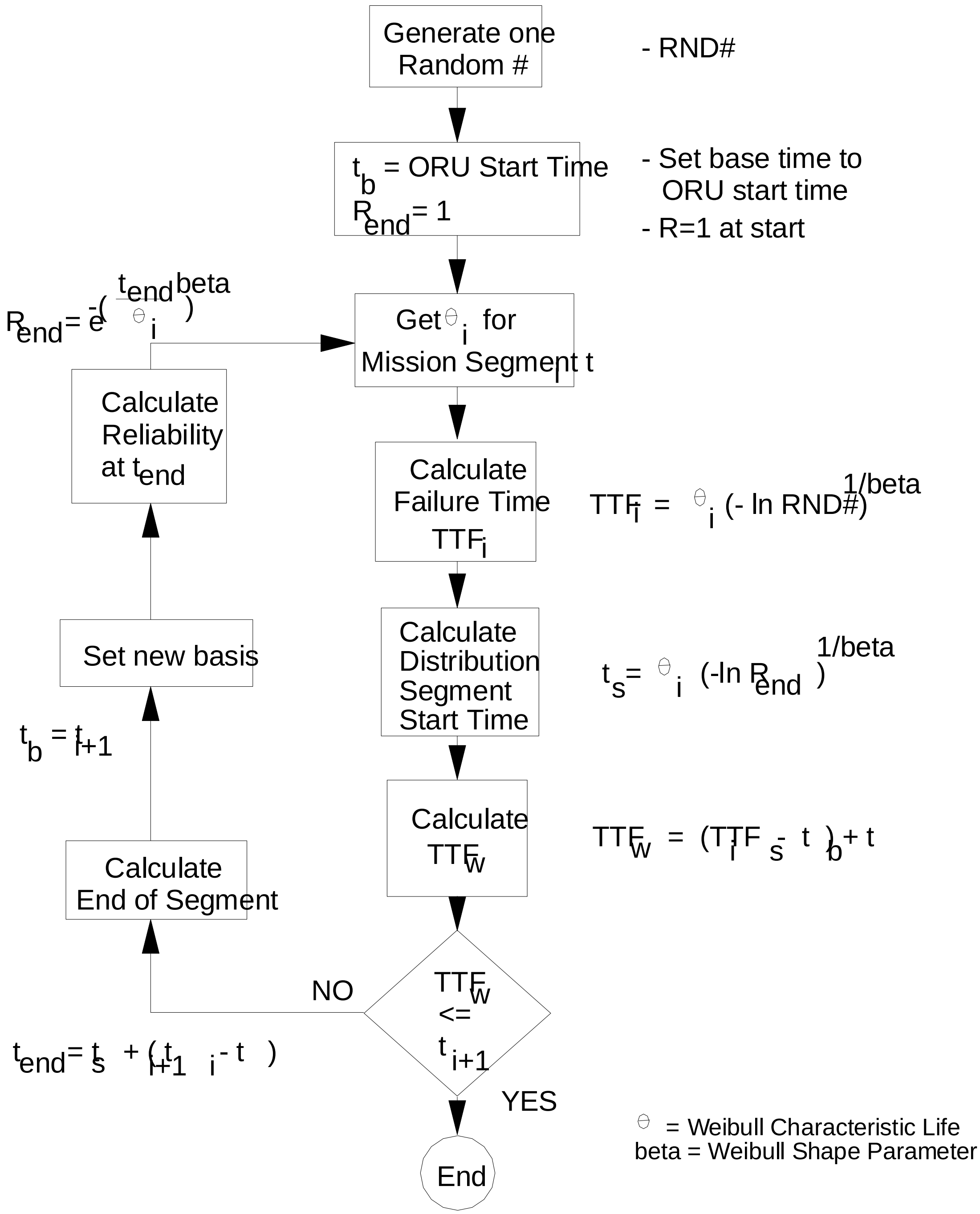


FIGURE 9 - MMH/Year and Resupply Mass Calculations